LONG-TERM MORPHOLOGICAL MODELING AT COASTAL INLETS

ALEJANDRO SANCHEZ[1], MITCHELL BROWN[2], TANYA BECK[3], RICHARD STYLES[4], HONGHAI LI[5]

1. *U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA. Alejandro.Sanchez@usace.army.mil.*
2. *U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA. Mitchell.E.Brown@usace.army.mil.*
3. *U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA. Tanya.M.Beck@usace.army.mil.*
4. *U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA. Richard.Styles@usace.army.mil.*
5. *U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA. Honghai.Li@usace.army.mil.*

Abstract: The U.S. Army Corps of Engineers' Coastal Modeling System (CMS) is used to simulate the long-term morphodynamics of coastal barrier-inlet systems. The CMS consists of an integrated numerical modeling system for simulating wave, current, water levels, sediment transport and morphology change. In order to quantify the physical effects of long-term, regional climactic changes in the environment, numerical morphodynamic models must be able to reproduce the known generic characteristics that drive barrier inlet processes, including equilibrium inlet dimensions and sediment budget for the tidal shoals. In this study, model results are presented for a 10-year simulation of an idealized inlet and bay system with dimensions similar to that of Humboldt Bay, CA. The model reproduces reasonably well several geomorphic and hydrodynamic features of the inlet at Humboldt Bay. The model results demonstrate the feasibility of applying the CMS for simulating long-term morphology at coastal inlets for practical applications.

Introduction

Coastal barrier-inlet systems are relatively short and narrow channels connecting the open ocean with sheltered bays, lagoons, or estuaries. Inlets are often artificially stabilized and dredged to maintain navigation pathways for commercial and recreational vessels. Modifications to the equilibrium state of the inlet, either by natural cause such as storms or relative sea level rise, or, by anthropogenic causes, can have a significant impact on sediment pathways and

adjacent shoreline lasting years to several decades. The complex and dynamic interactions of tidal flow, waves, and morphology at barrier-inlet systems extend over a wide range of temporal and spatial scales. Thus, the prediction of the morphodynamic processes at coastal inlets is a challenging, but crucial task for coastal sediment management, navigation channel maintenance, and beach erosion protection as these critical projects are all linked to barrier-inlet processes. This predictive capability must also include some components of long-term, regional climactic changes in the environment. Numerical morphodynamic models must be able to reproduce the known generic characteristics that drive barrier inlet processes, including equilibrium inlet dimensions and sediment budget for the tidal shoals, to validate their use in predicting long-term modifications to physical processes.

The U.S. Army Corps of Engineers' Coastal Modeling System (CMS) is a suite of two-dimensional horizontal (2DH) coupled numerical models for simulating waves, hydrodynamics, salinity and sediment transport, and morphology change (Lin et al., 2008; Sánchez et al., 2014). The CMS is designed to provide coastal engineers and scientists an efficient tool for the understanding of coastal processes and for the design and management of coastal inlets, navigation channels, ports, harbors, coastal structures, and adjacent beaches.

CMS-Flow is a 2DH depth-integrated model developed for simulating wave-averaged hydrodynamics and nonuniform sediment transport and morphology change in coastal waters. The hydrodynamic model includes advection, wave-enhanced turbulent mixing and bottom friction; wave-induced volume flux; wind, atmospheric pressure, wave, river, and tidal forcing; and Coriolis-Stokes force. The sediment transport model simulates nonequilibrium total-load transport of nonuniformly sized sediments, and includes flow and sediment transport lags, hiding and exposure, bed-material sorting, bed-slope effects, nonerodible beds, and avalanching.

This paper presents the long-term simulation of an idealized inlet and bay system representative of existing inlets around the continental U.S. The objectives of the study are to (1) validate the CMS using basic morphologic features such as cross-sectional area, ebb and flood shoal volumes and hydrodynamic variables such as mean peak current velocity and tidal prism, and (2) demonstrate the feasibility of applying the CMS for simulating long-term morphology change at coastal inlets. Several model runs are carried out with different initial geometries, and model setup (e.g., sediment transport formulas) to investigate the controlling geomorphic parameters and the applicability of the CMS to long-term morphology change. Although several inlets have been tested, this analysis here is focused on the results of one inlet and bay system with dimensions based on Humboldt Bay, CA.

Methodology

Idealized Inlet Geometry

The initial inlet and bay geometry is designed to match field measurements of length, and width, area, average depth. Initially the ebb and flood shoals are not included in the bathymetry. The beach profile is assigned an equilibrium beach profile also based on measured bathymetry. An example of an idealized inlet with dimensions similar to Humboldt Bay, CA is shown in Figure 1. The inlet length and width are 1,100 meters (m) and 570 m, respectively. The initial inlet cross-sectional area is 6800 m^2. The bay area and initial depth are 64.8 Million (M) m^2 and 3.4 m, respectively. As shown in Figure 1, the initial inlet and bay geometry are very simplified and do not include many of the geomorphic features of the actual inlet and bay system such as the asymmetric bay area and the hypsometric curve (change and wetted bay area with respect to water level). However, the idealized inlet and bay system is considered adequate the purposes of the study which is to capturing the most basic geomorphic and hydrodynamic features of the system.

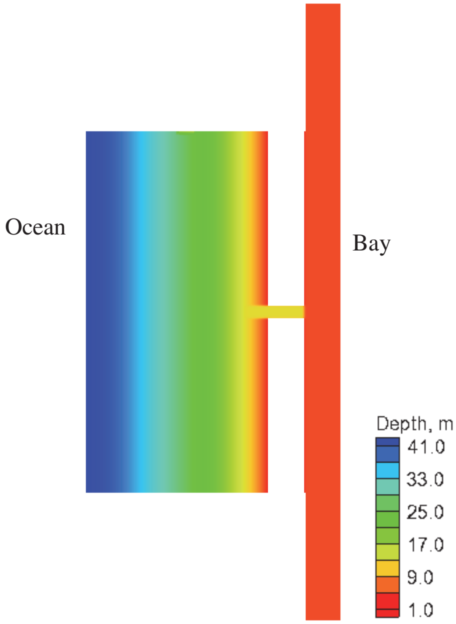

Figure 1. Computational domain and bathymetry of the idealized inlet with dimensions similar to Humboldt Bay, CA.

Hydrodynamics

For the simulations presented in this paper, atmospheric forcing, and the wave-volume flux are ignored and the governing hydrodynamic equations may be written as

$$\frac{\partial h}{\partial t}+\frac{\partial (hU_j)}{\partial x_j}=0 \tag{1}$$

$$\begin{aligned}\frac{\partial (hU_i)}{\partial t}+\frac{\partial (hU_iU_j)}{\partial x_j}-\varepsilon_{ij}f_chU_j=-gh\frac{\partial \overline{\eta}}{\partial x_i}\\+\frac{\partial}{\partial x_j}\left(\nu_t h\frac{\partial U_i}{\partial x_j}\right)-\frac{1}{\rho}\frac{\partial}{\partial x_j}\left(S_{ij}+R_{ij}\right)-m_b\frac{\tau_{bi}}{\rho}\end{aligned} \tag{2}$$

where t = time (s), h = water depth (m), U_i = current velocity (m/s), f_c = Coriolis parameter (rad/s) equal to $f_c=2\Omega\sin\phi$ where Ω is the earth's angular velocity (rad/s) of rotation and ϕ = latitude (rad). $\varepsilon_{ij}=1$, for $i=1,\ j=2$, $\varepsilon_{ij}=-1$, for $i=2,\ j=1$, and $\varepsilon_{ij}=0$, otherwise, ρ = sea water density (~1025 kg/m^3); g = gravitational constant (~9.81 m/s^2), ν_t = horizontal turbulent eddy viscosity (m^2/s), τ_{bi} = wave-averaged bed shear stress (Pa), m_b = bed slope coefficient, S_{ij} = wave radiation stress (Pa m), and R_{ij} = surface roller stress (Pa m). The governing hydrodynamic equations are solved on a Cartesian grid using a fully implicit finite-volume method. For more details on hydrodynamic calculations, the reader is referred to Sánchez et al., (2014).

Sediment Transport

Sediment transport is simulated using the 2DH total-load sediment transport equation which for the case of a single grain size is given by (Sánchez and Wu 2011)

$$\frac{\partial}{\partial t}\left(\frac{hC_t}{\beta_t}\right)+\frac{\partial (hU_jC_t)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\nu_s h\frac{\partial (r_sC_t)}{\partial x_j}\right]+\alpha_t\omega_s\left(C_{t*}-C_t\right) \tag{3}$$

where C_{tk} = concentration of total load (kg/m^3), C_{tk*} = equilibrium concentration of total load (kg/m^3), α_t = total-load adaptation coefficient, ν_s =

sediment mixing coefficient (m²/s), ω_s = sediment fall velocity (m/s), r_s = fraction of suspended sediments, and β_t = total-load correction factor. The total-load adaptation coefficient is calculated as $\alpha_t = Uh/(L_t \omega_s)$, where L_t is the total-load adaptation length (m). The correction factor, β_t, accounts for the vertical distribution of the suspended sediment concentration and velocity profiles, as well as the fact that bed load usually travels in a velocity slower than the depth-averaged current velocity. By definition, β_t is the ratio of the depth-averaged total-load and flow velocities. The bed change is calculated as

$$\rho_s\left(1-p'_m\right)\frac{\partial z_b}{\partial t} = \alpha_t \omega_s\left(C_t - C_{t*}\right) + \frac{\partial}{\partial x_j}\left(D_s q_b \frac{\partial z_b}{\partial x_j}\right) \tag{4}$$

where ρ_s = sediment density (kg/m³), p'_m = bed porosity, z_b = bed elevation (m), D_s = empirical bed-slope coefficient (constant), $q_b = hUC_t(1-r_s)$ = bed load mass transport rate (kg/m/s). It is noted that the CMS is capable of simulating multiple grain sizes but for simplicity this feature is not utilized in this study and is left for future work. The sediment transport equations are solved using a fully implicit finite-volume method on the same grid and the same time step as the hydrodynamic equations. For more details of the sediment transport model the reader is referred to Sánchez et al., (2014).

Model Setup

The hydrodynamic model CMS-Flow is forced at the offshore boundary with the nine largest water level tidal constituents from the NOAA (National Oceanographic and Atmospheric Administration) tidal gauge station located at North Spit, CA. Since the present simulations represent idealized simulations, the nodal factor and equilibrium arguments are not included in the simulations. The simulations are forced with constant waves conditions representing the mean wave climate. No river flow, wind or atmospheric pressure is included. The wave model is forced with a 2-m significant wave height, 10-second (s) peak wave period, and 300º incident wave angle (approximately west-northwest). The Manning's roughness coefficient is set to a constant value of 0.02 s/m$^{1/3}$. Based on a sensitivity analysis a time step of 15 minutes (min) in combination with the second-order temporal scheme is found to be sufficiently accurate and comparable to the first-order scheme with a time step of 5 min. A 1-hr steering interval between the wave and flow models is also determined based on a sensitivity analysis. All simulations were run on nonuniform Cartesian grids. The grid resolution varied between 50 m at the inlet to about 470 m offshore (see Figure 2).

The sediment transport model is run with a constant grain size of 0.2 mm, and the Soulsby-van Rijn sediment transport capacity formula (Soulsby, 1997).

In order to speed up the simulation, a morphological acceleration factor of 10 is used for all simulations. The morphological acceleration multiplies the bed change at each time step to effectively speed-up the morphology change (see for example Roelvink and Reniers, 2012). Given that the model is forced with constant wave conditions and tidal constituents, this is considered a reasonable approximation. Sensitivity tests confirmed that the morphological acceleration factor of 10 produced almost identical results to a factor of 1.

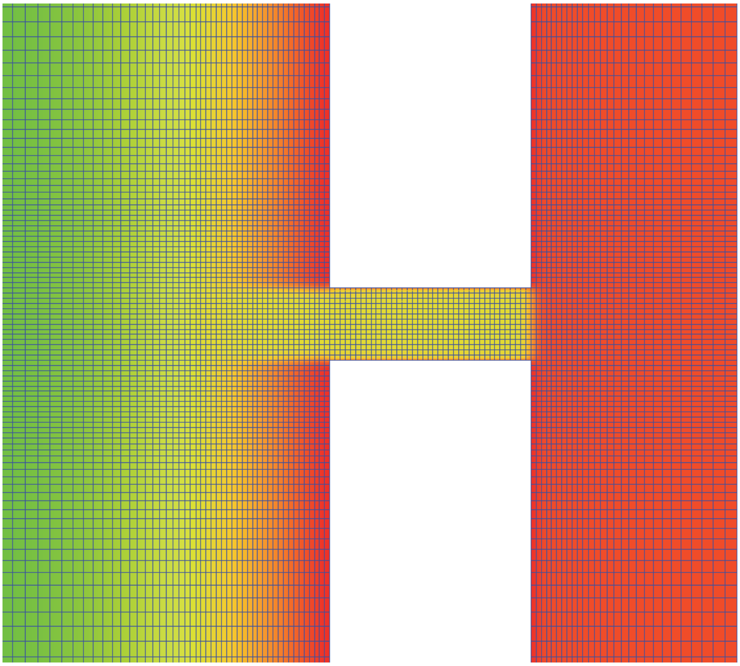

Figure 2. Idealized inlet with dimensions similar to Humboldt Bay, CA showing (a) the computational domain and (b) the grid resolution near the inlet.

Results and Discussion

A close-up of the initial bathymetry and simulated 10-year bathymetry are presented in Figure 3a. The simulated temporal evolution of the ebb shoal, flood shoal, and inlet volumes are presented in Figure 3b. For comparison the real bathymetry of Humboldt Bay, CA is shown in Figure 4. The model predicts a net

erosion of the shorelines on both sides of the inlet. This is due to the asymmetry in flood and ebb currents which produce a net sediment transport directed towards the inlet along the adjacent beaches. However, the shoreline erosion on the south side of the inlet is larger which is consistent with the incident wave direction. The ebb shoal is asymmetric with a larger volume on the northern side of the inlet axis. At least part of the inlet asymmetry is attributed to the Coriolis effect which in this case deflects the ebb jet towards the north.

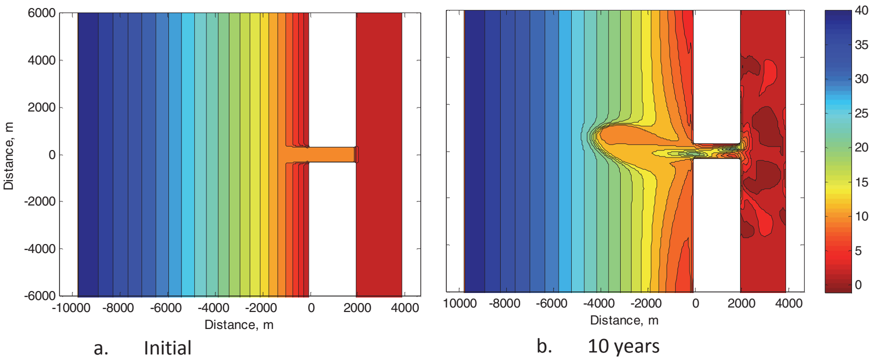

Figure 3. Idealized inlet representing Humboldt Bay, CA. Initial bathymetry (a) and bathymetry after 10 years (b). Color contours indicate water depth in meters.

As observed in the field for Humboldt Bay, the flood shoal is not well defined with relatively small shoals separated by channels. The computed flood shoal volume is estimated at 5.8 M m^3 which agrees well with the 3-6 M m^3 estimated from field bathymetry. The maximum depth along the inlet channel of approximately 20 m also agrees well with field measurements of 21 m.

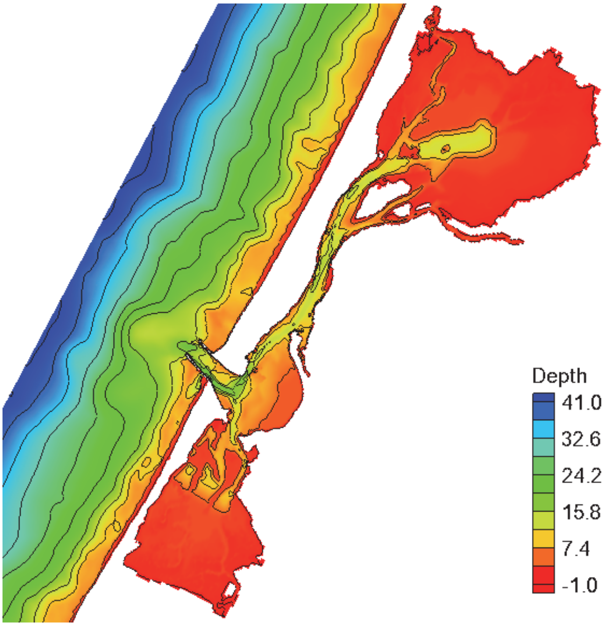

Figure 4. Humboldt Bay, CA bathymetry.

A comparison of several geomorphic and hydrodynamic variables for the idealized inlet and Humboldt Bay, CA is presented in Table 1. In general the analyzed basic geomorphic and hydrodynamic variables of the idealized inlet compare relatively well to those of Humboldt Bay, CA.

Table 1. Comparison of several geomorphic and hydrodynamic variables between Humboldt Bay, CA and the representative idealized inlet.

Variable	**Humboldt Bay, CA**	**Idealized Inlet after 10 years**
Tidal prism, M m^3	74 *	88
Mean spatially averaged peak current velocity, m/s	1.1–1.3 †	1.3
Inlet cross-sectional area below MTL, m^2	7,016	7,500
Ebb shoal volume, M m^3	24–49	24
Flood shoal volume, M m^3	3– 6	5.8

* Coasta (1982), † Claasen (2003)

The model reproduces the general geomorphic features of Humboldt Bay. The ebb shoal volume is in the lower range of the estimated amount from field measurements. Figure 5 shows the temporal evolution of the ebb and flood shoals and inlet volume. The flood shoal volume seems to stabilize after approximately 4 years. However the ebb shoal and inlet do not appear to reach equilibrium after 10 years and thus longer simulations are needed. Future work will focus on running longer simulations, running with real wave spectra time series, and evaluating the model sensitivity to initial bathymetry and sediment transport options.

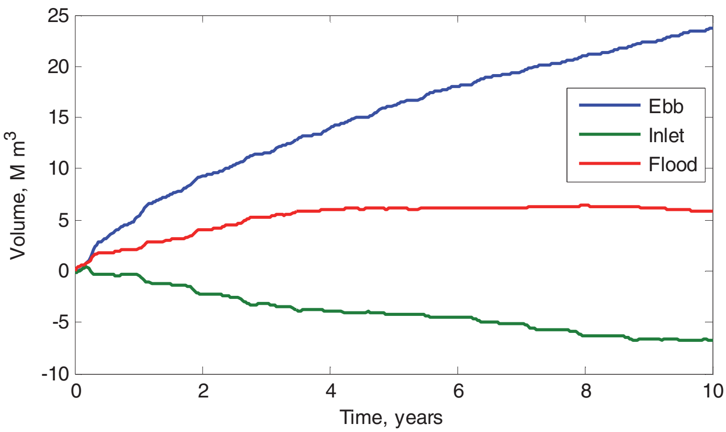

Figure 5. Comparison of measured and computed volume for the ebb shoal, inlet, and flood shoal.

Finally, the simulation takes about 10 hrs (wall clock time) to run on two threads with a 2.9 GHz processor. Therefore, a 10-year simulation with a morphologic acceleration factor of 10 representing 100-years of morphology change takes approximately 4.2 days to run.

Conclusion

The USACE CMS has been used to simulate long-term coastal inlet morphology change of idealized inlets representing real inlets of the continental U.S. Results are shown here for an inlet representative of Humboldt Bay, CA in terms of the inlet and bay dimensions. The model is validated by comparing computed values of tidal prism, mean peak current velocity, inlet cross-sectional area, and ebb shoal volume with field measurements and values reported from literature. The model results and computational speed demonstrate the feasibility of applying the CMS for long-term simulation of morphology change at coastal inlets.

Acknowledgements

This work was conducted in part through funding from the *Coastal Modeling System* work unit of the Coastal Inlets Research Program of the U.S. Army Engineers Research and Development Center, Vicksburg, MS. Permission was granted by the Chief, U. S. Army Corps of Engineers, to publish this information. We appreciate the guidance and support of Dr. Julie D. Rosati, Program Manager of the Coastal Inlets Research Program.

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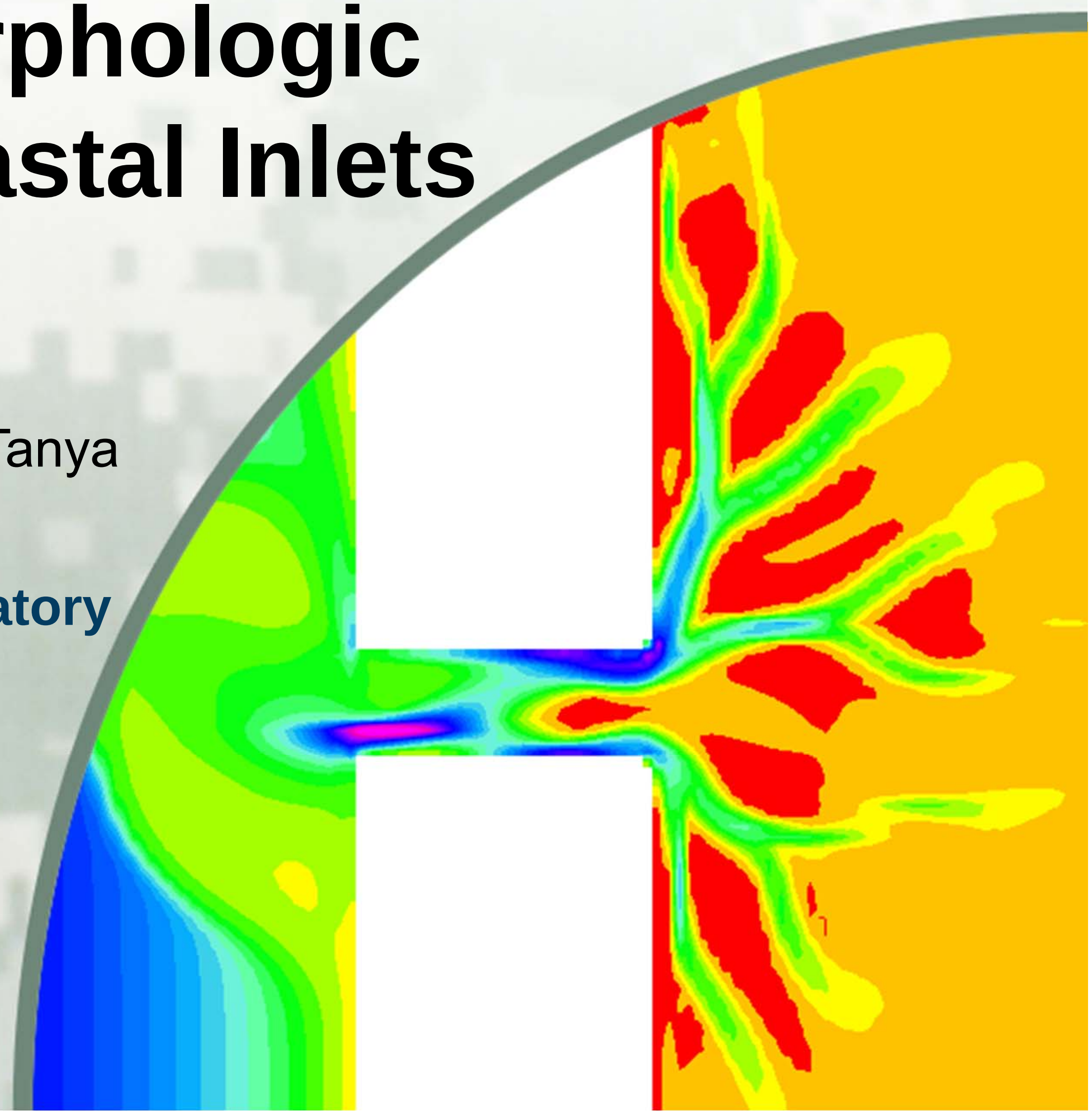
Long-term Morphologic Modeling at Coastal Inlets

Alex Sánchez

Richard Styles, Mitchell Brown, Tanya Beck, and Honghai Li

Coastal and Hydraulics Laboratory
US Army Corps of Engineers



Introduction

- Motivation:
  - ► Prediction of morphodynamic processes at coastal inlets is challenging but crucial for coastal sediment management, navigation, channel maintenance, and breach erosion protection
- Issue:
  - ► Difficult to conduct meaningful long-term validation of morphodynamic models using real data
- Approach:
  - ► Simulate idealized inlets representing 9 US inlets and compare inlet evolution, characteristics, and features with the actual inlets empirical formulas (soft validation)

Introduction: Coastal Modeling System

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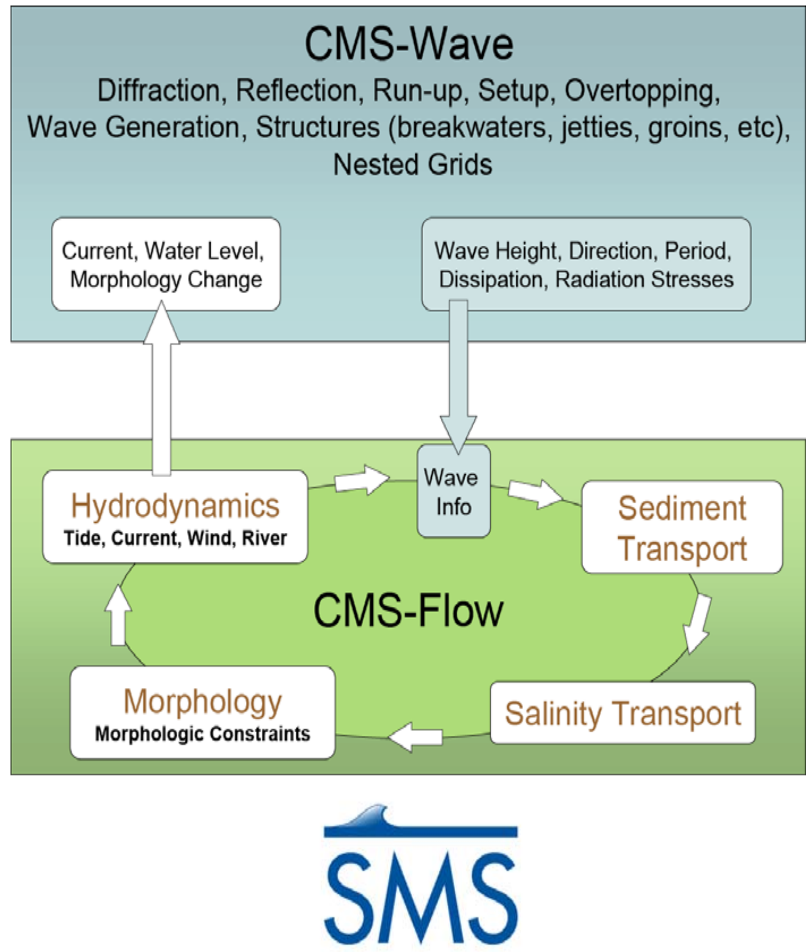
- Hydrodynamics:
  - 2DH shallow-water equations
  - Fully implicit, finite-volume method
  - Non-uniform or Telescoping Cartesian grids
- Sediment Transport
  - Inline
  - Total-load non-equilibrium sediment transport
  - Erosion/deposition calculated using an adaptation approach
  - Several options for transport capacity formula
- Waves
  - Spectral wave-action balance equation
  - Implicit finite-difference method



Empirical Relations

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- Cross-sectional area
  - ▸ O'brien (1931, 1969), Kraus (1998), Jarrrett (1976), van der Kreeke (1992), Powell et al. (2006), etc.

$$A = CP^n$$

$A \rightarrow$ Cross-sectional area $[m^2]$

$P \rightarrow$ Tidal prism $[m^3]$

$C \rightarrow 8.83\times10^{-6} - 1.88\times10^{-3}\ [m^{-1}]$

$n \rightarrow 0.81 - 1.10\ [-]$

- Ebb tidal shoal volume
  - ▸ Walton and Adams (1976)

$$V_{ebb} = aP^b$$

$a \rightarrow 5.3\times10^{-3} - 8.4\times10^{-3}$

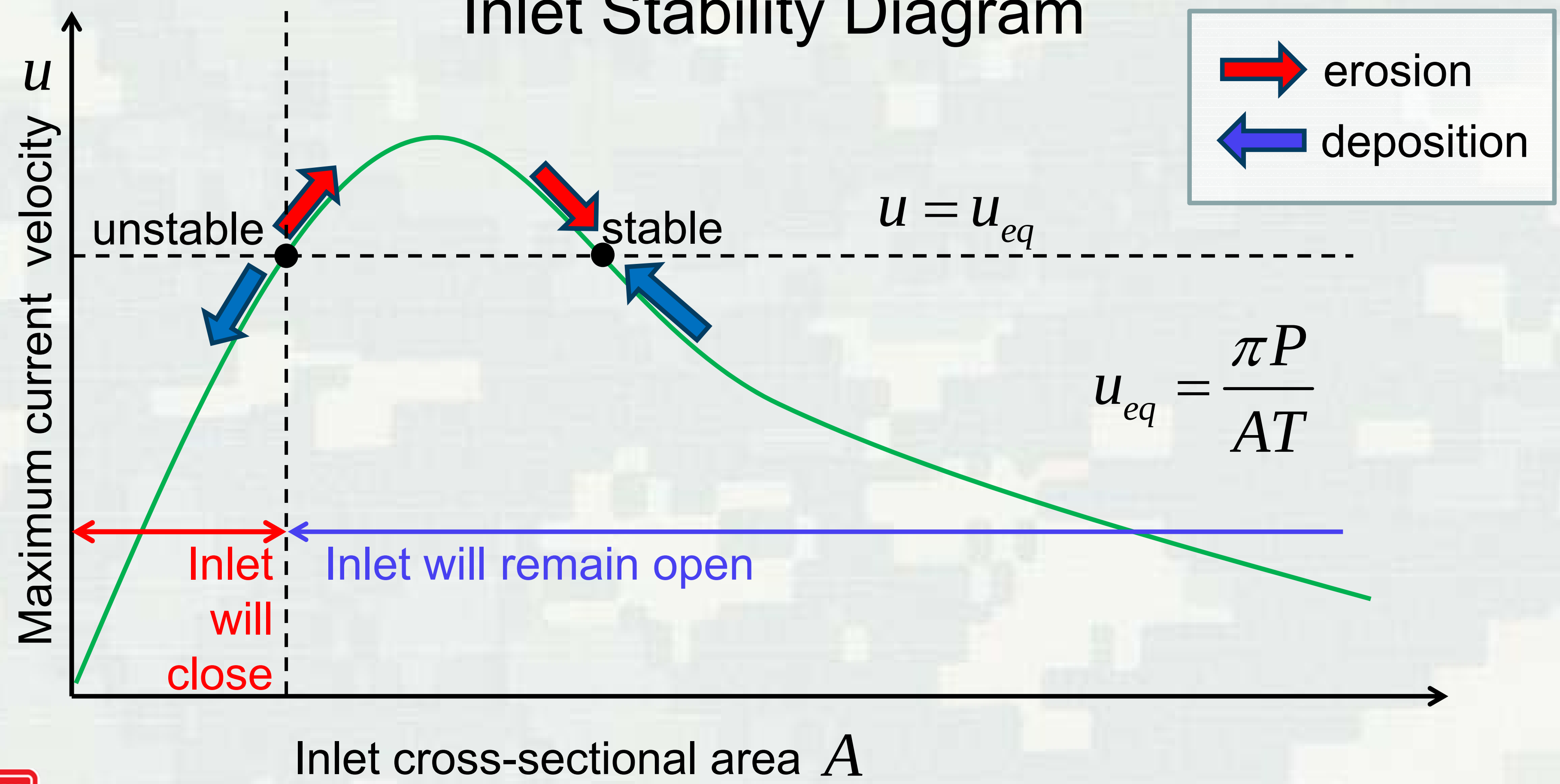
$b \rightarrow 1.23$

  - ▸ Hicks and Hume (1996)

$$V_{ebb} = 1.37\times10^{-3} P^{1.32} (\sin\theta)^{1.33}$$

Inlet Stability Analysis

Escoffier's (1940)
Inlet Stability Diagram



Methods: Base Inlets

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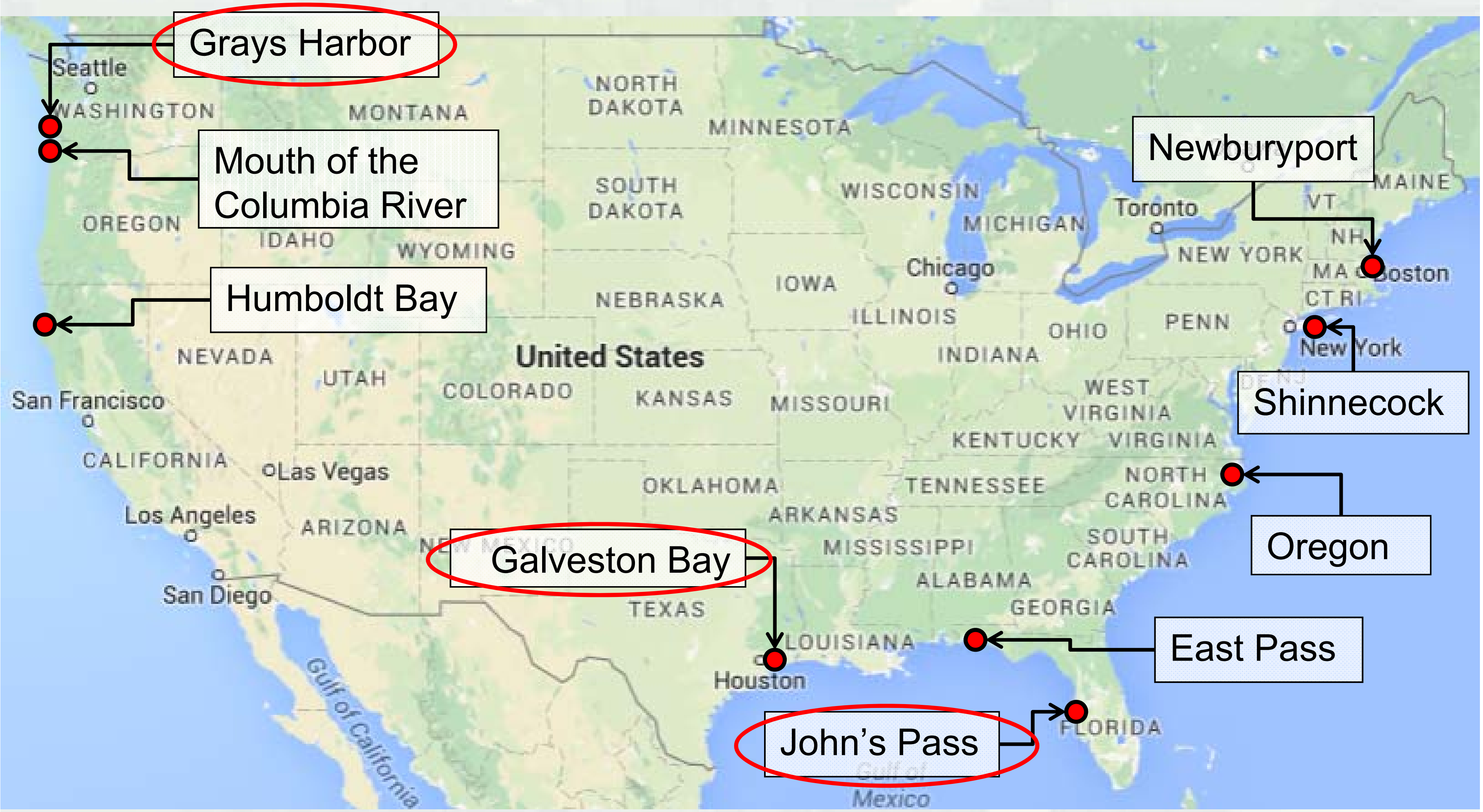

Methods: Idealized Inlets

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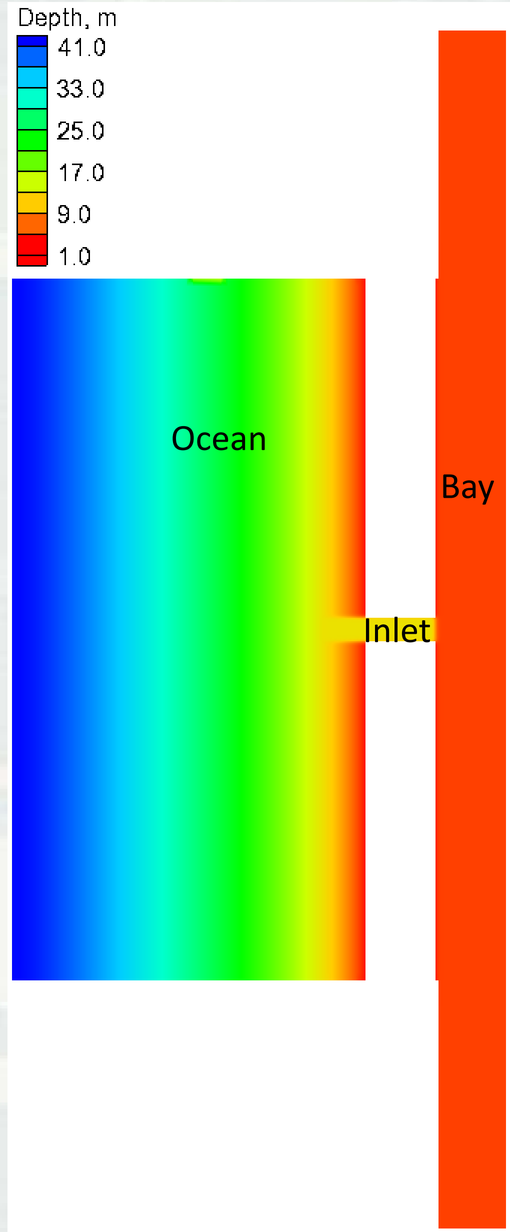
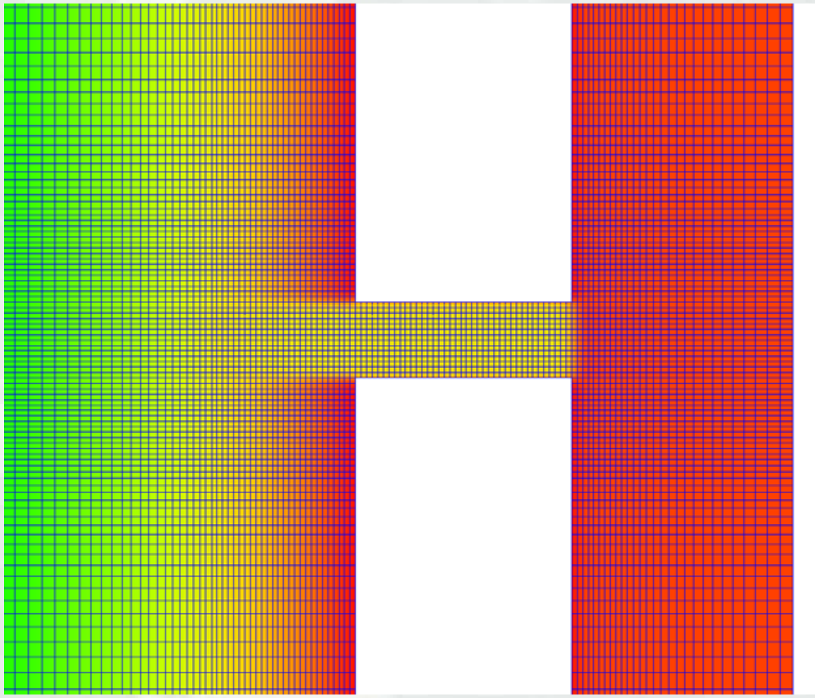
- Initial Morphology
  - Equilibrium offshore profile based on measured bathymetry or median grain size
  - Flat rectangular bay with dimensions based on actual inlet. Bay width and length adjusted to match actual bay area
  - Flat rectangular inlet with width and area matching actual inlet
- Water levels
  - Tidal constituents
- Waves
  - Representative year based on mean sediment transport rate estimated from the CERC formula and nearby buoy data



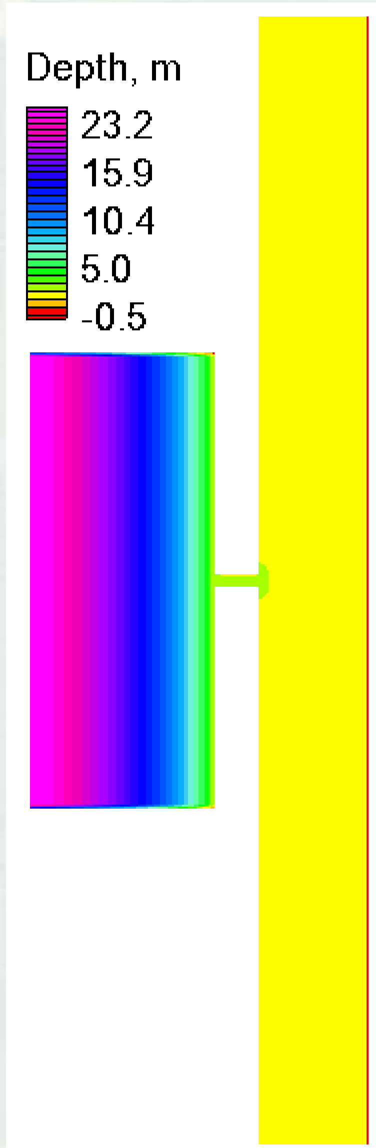
Methods: Model Setup

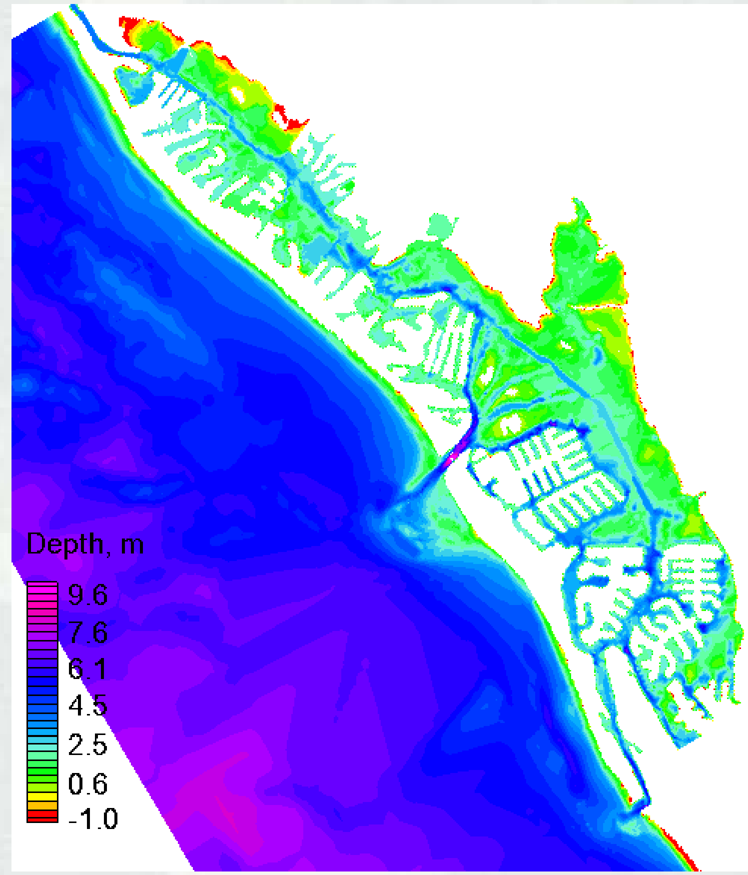
- Flow
  - Manning's n = 0.025 s/m$^{1/3}$
  - Coriolis
- Sediment transport
  - Single representative grain size
  - Morphologic acceleration factor = 10
- Time stepping
  - Flow and sediment: 15 min
    - Second-order scheme
  - Waves: 1 hr
- Grids
  - Same for flow, sediment, and waves
  - Resolution
    - At least 10 cells across inlet



John's Pass, FL

- Waves
  - H_{mo} = 0.73 m
  - T_p = 4 s
- Tidal range
  - 0.43 m
- Bay Dimensions
  - Area = 4.5e7 m^2
  - Length = 27 km
  - Width = 19 km
- Inlet
  - Area = 845 m^2
  - Width = 300 m





Johns Pass, FL

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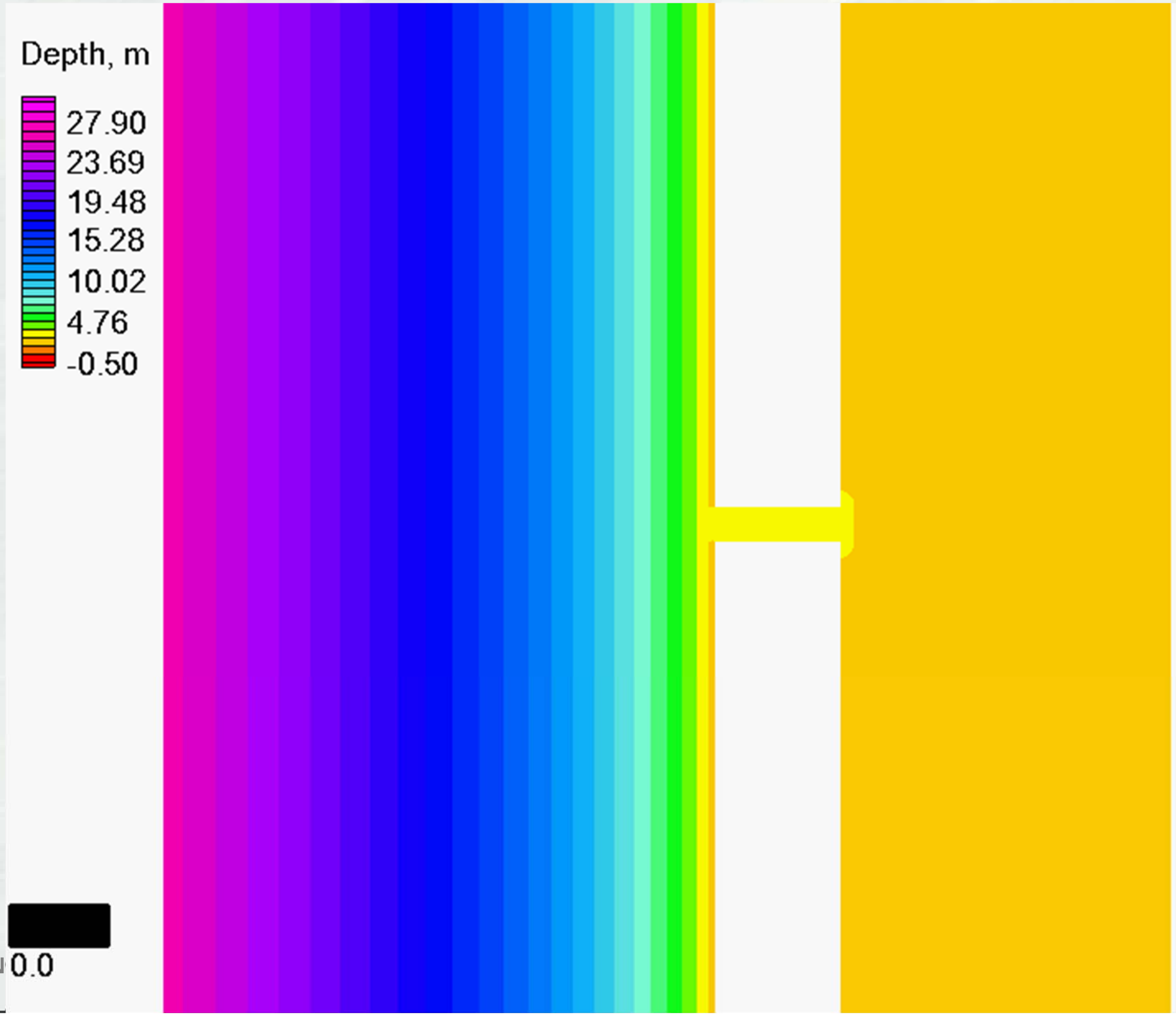
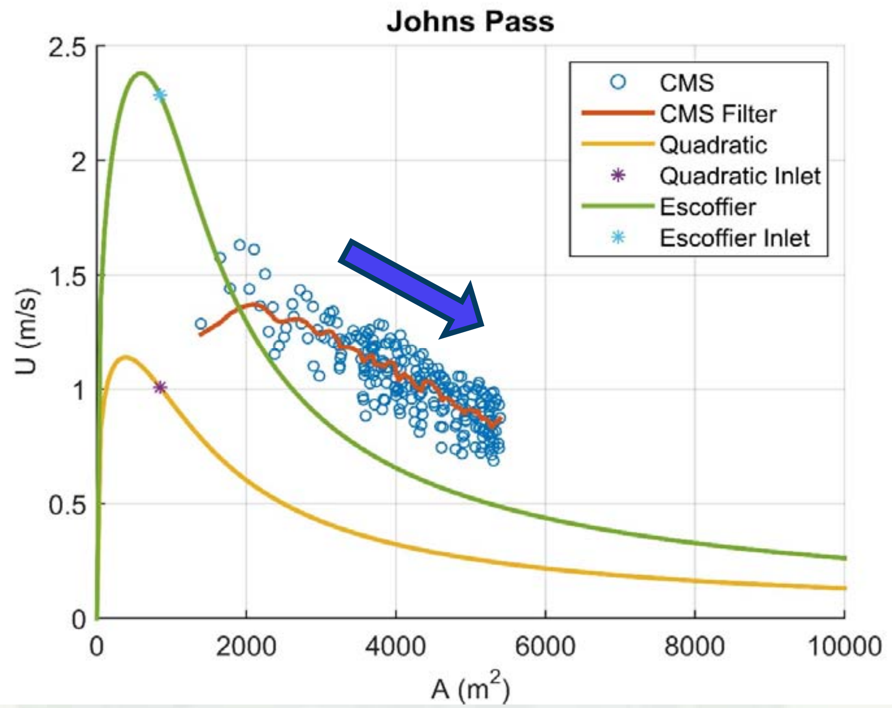
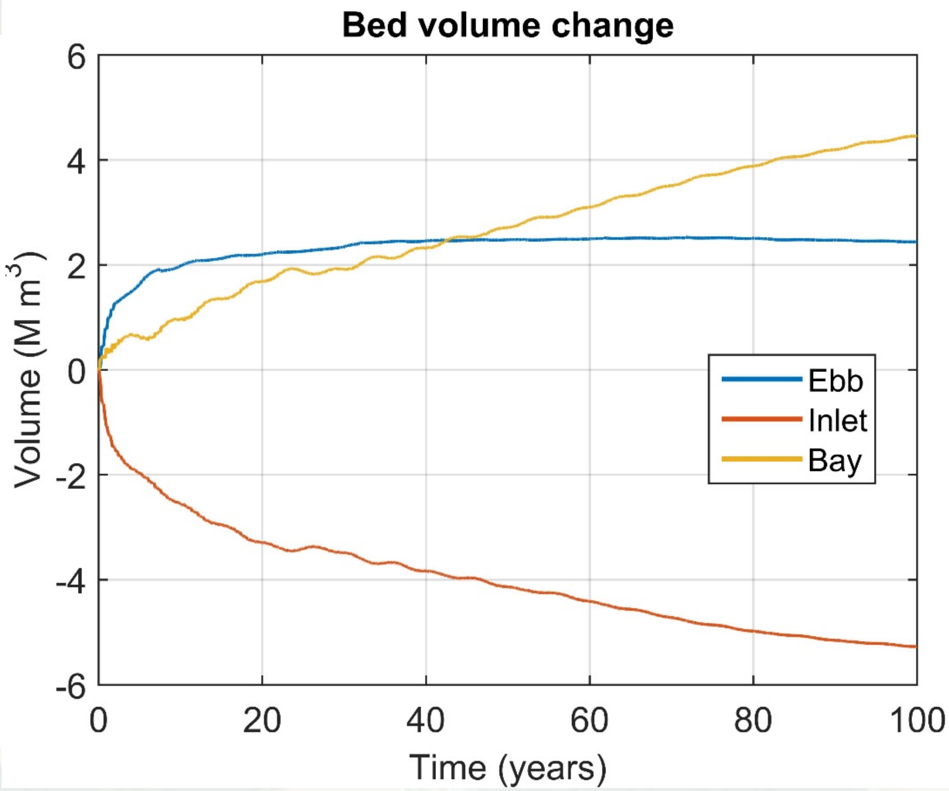


BUILDIN

Results: Johns Pass, FL

Flood dominant





- Actual ebb shoal volume
  - ► 2.1 to 2.3 M m^3

Results: Johns Pass, FL

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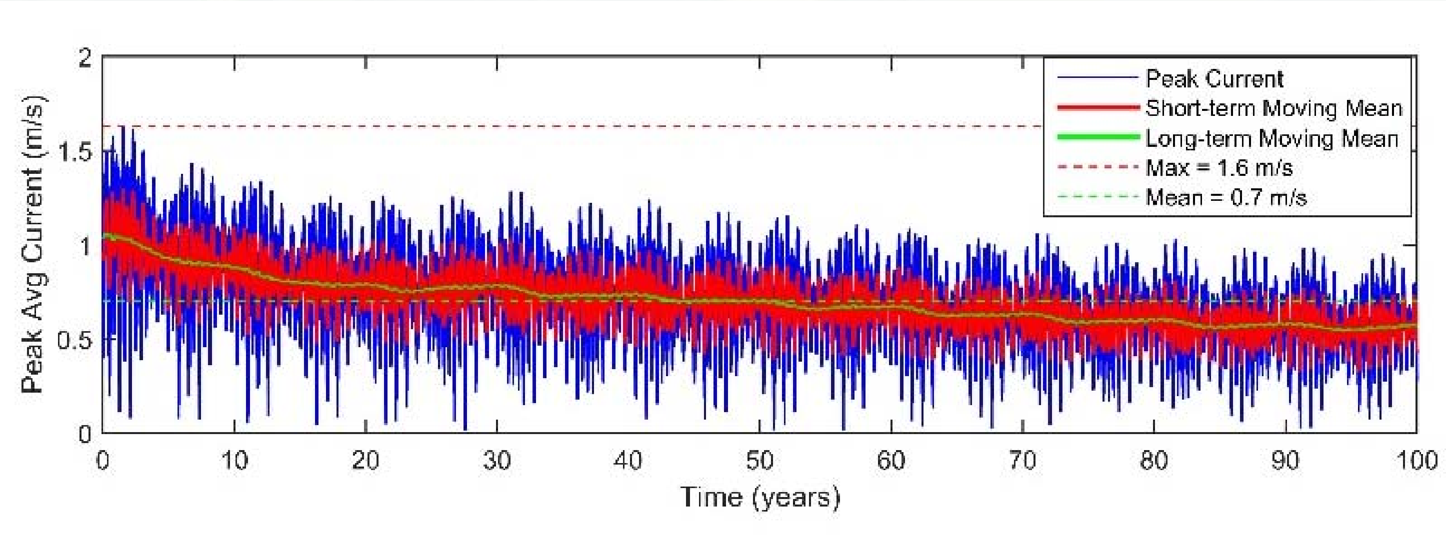
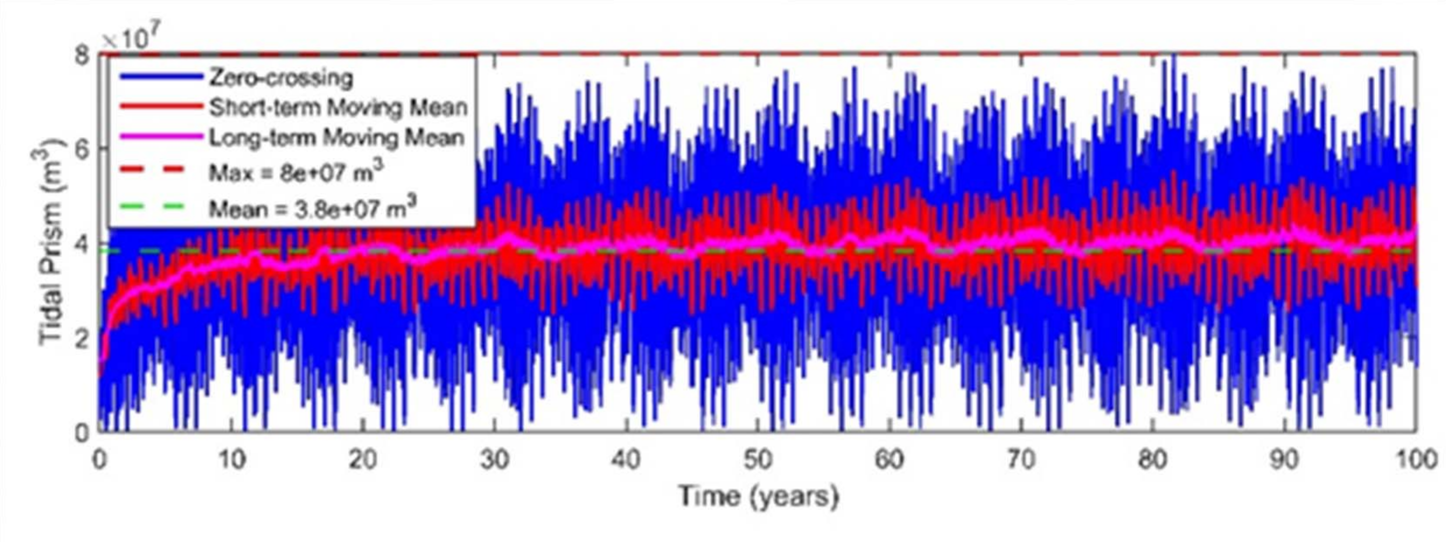
Actual peak current velocity

~1.2 m/s



Tidal Prism:

2.1×10^7 m^3



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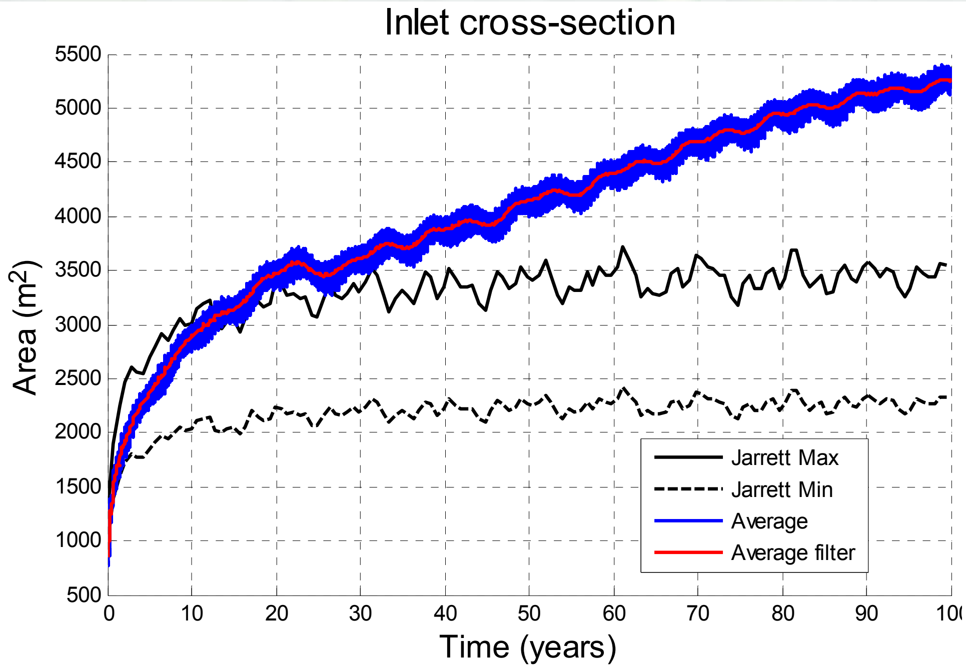
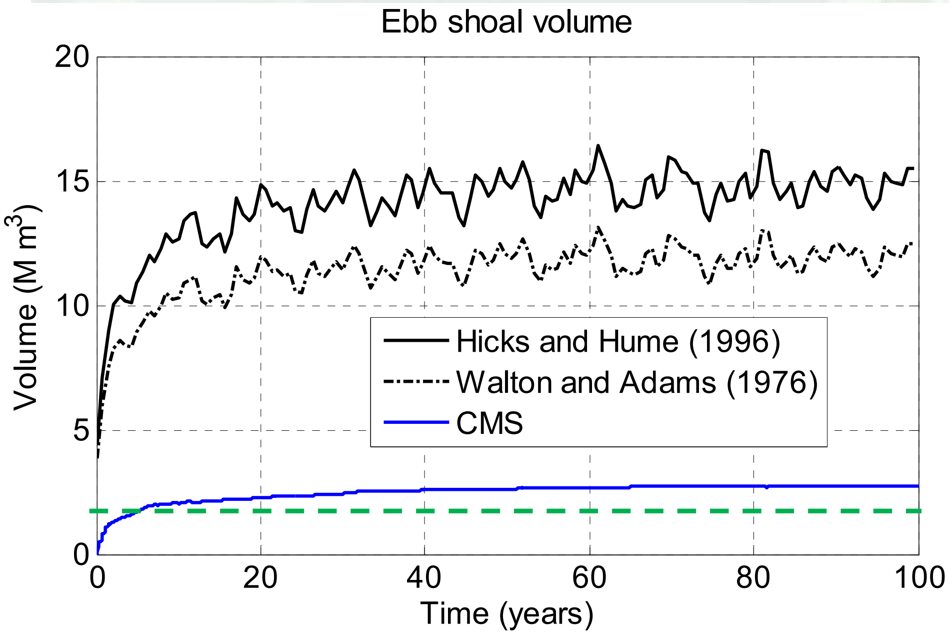
Results: Johns Pass, FL



- Inlet does not reach equilibrium
- Ebb shoal does reach equilibrium but is underestimated



Results: Grays Harbor

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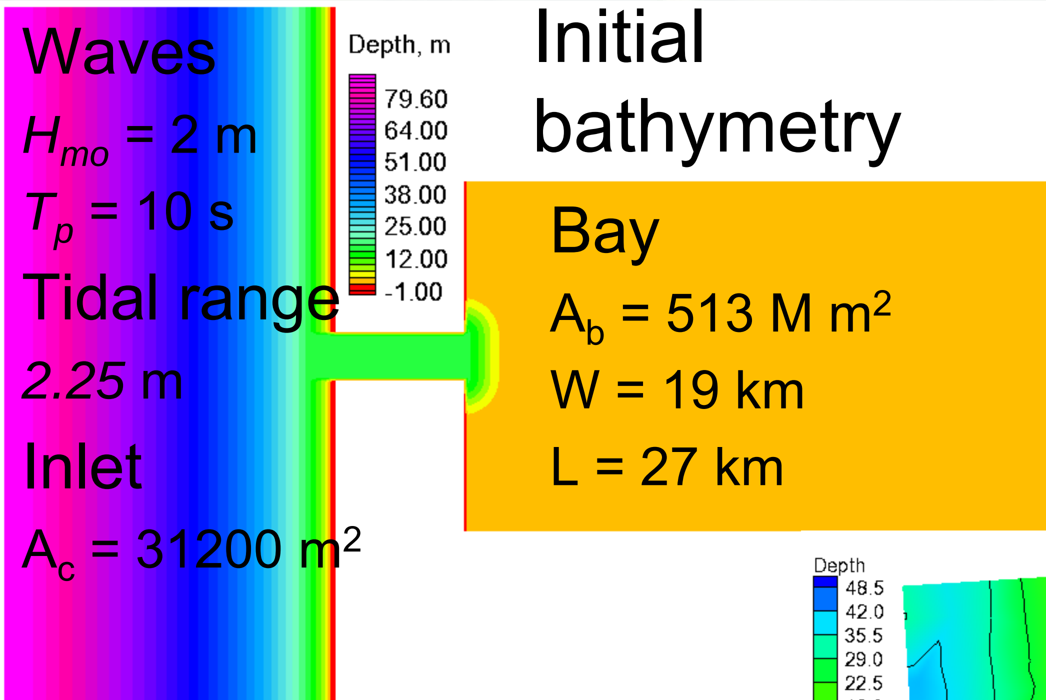


Waves

H_{mo} = 2 m

T_p = 10 s

Tidal range

2.25 m

Inlet

A_c = 31200 m^2

Initial bathymetry

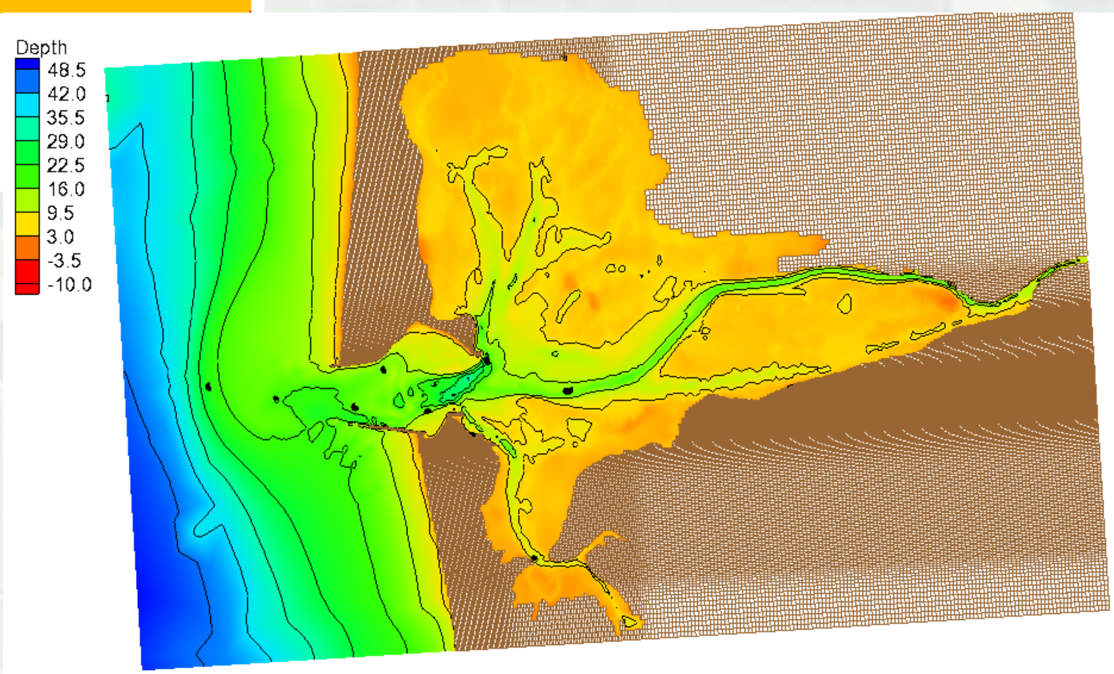
Bay

A_b = 513 M m^2

W = 19 km

L = 27 km

Actual bathymetry



Results: Grays Harbor, WA

CIRP

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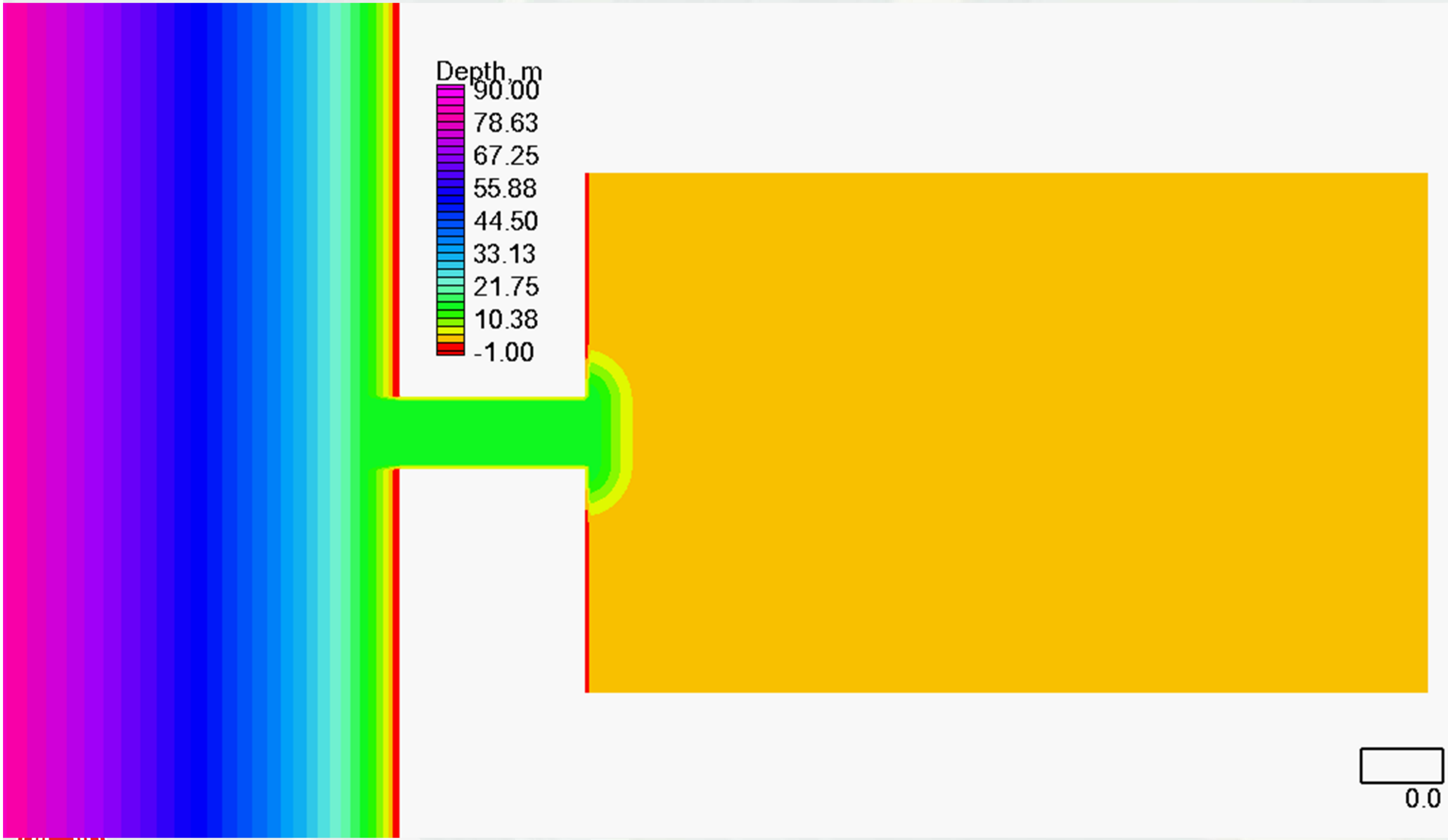
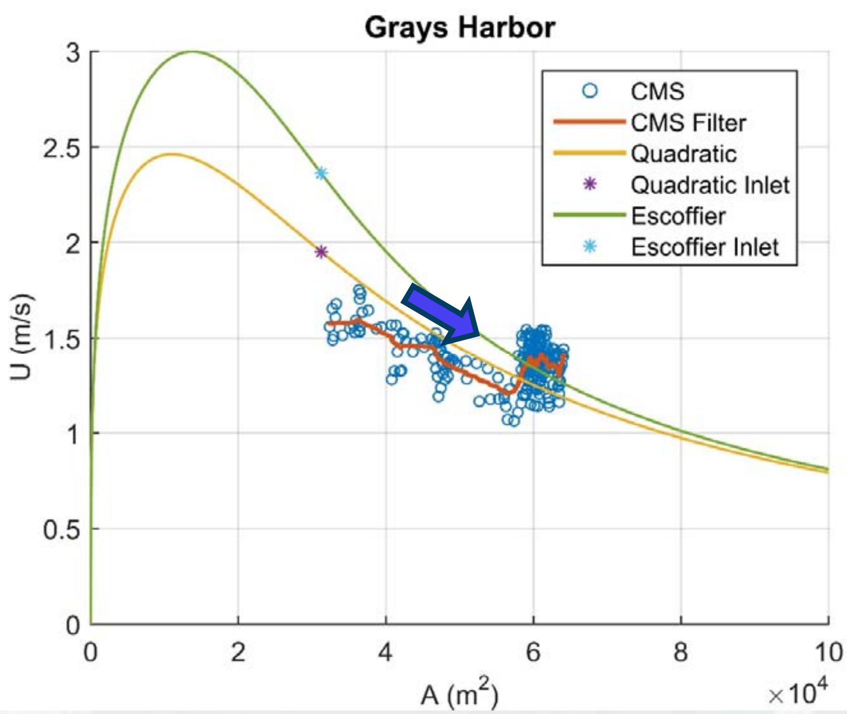
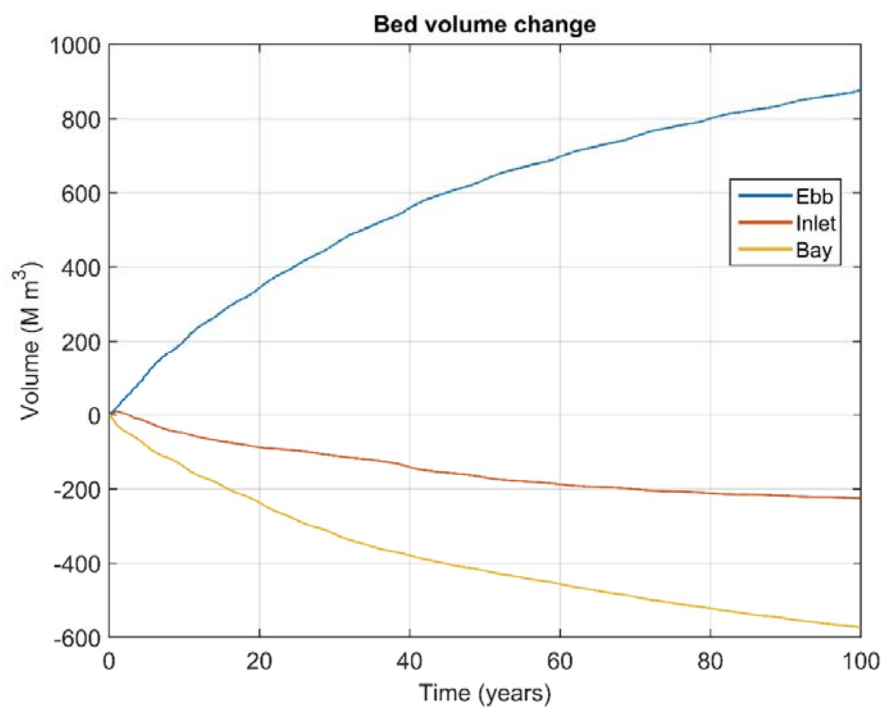


Grays Harbor, WA

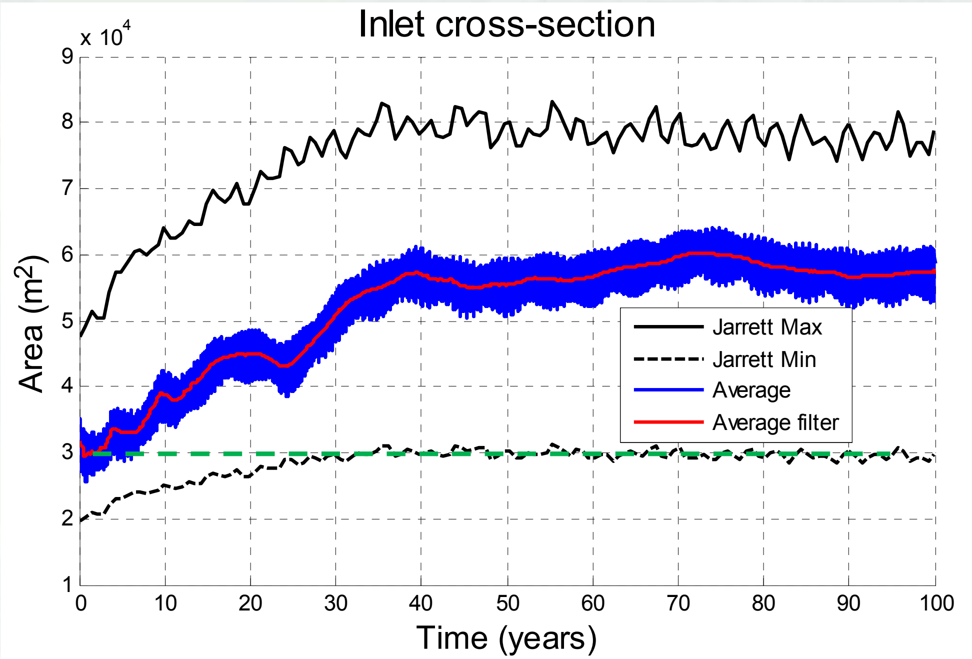


Equilibrium cross-sectional area of idealized inlet larger than initial condition

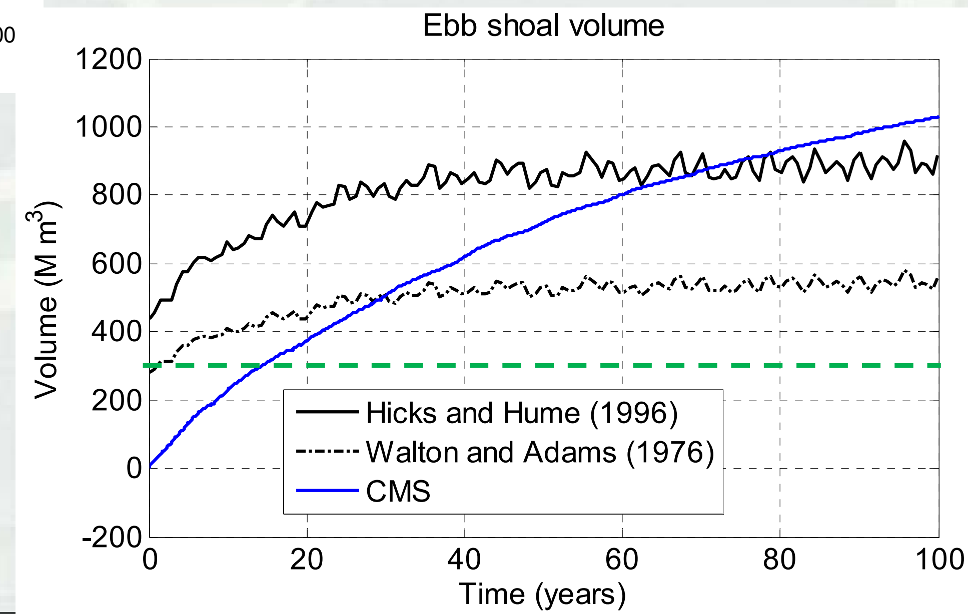


Inlet still evolving after 100 years

Results: Grays Harbor, WA

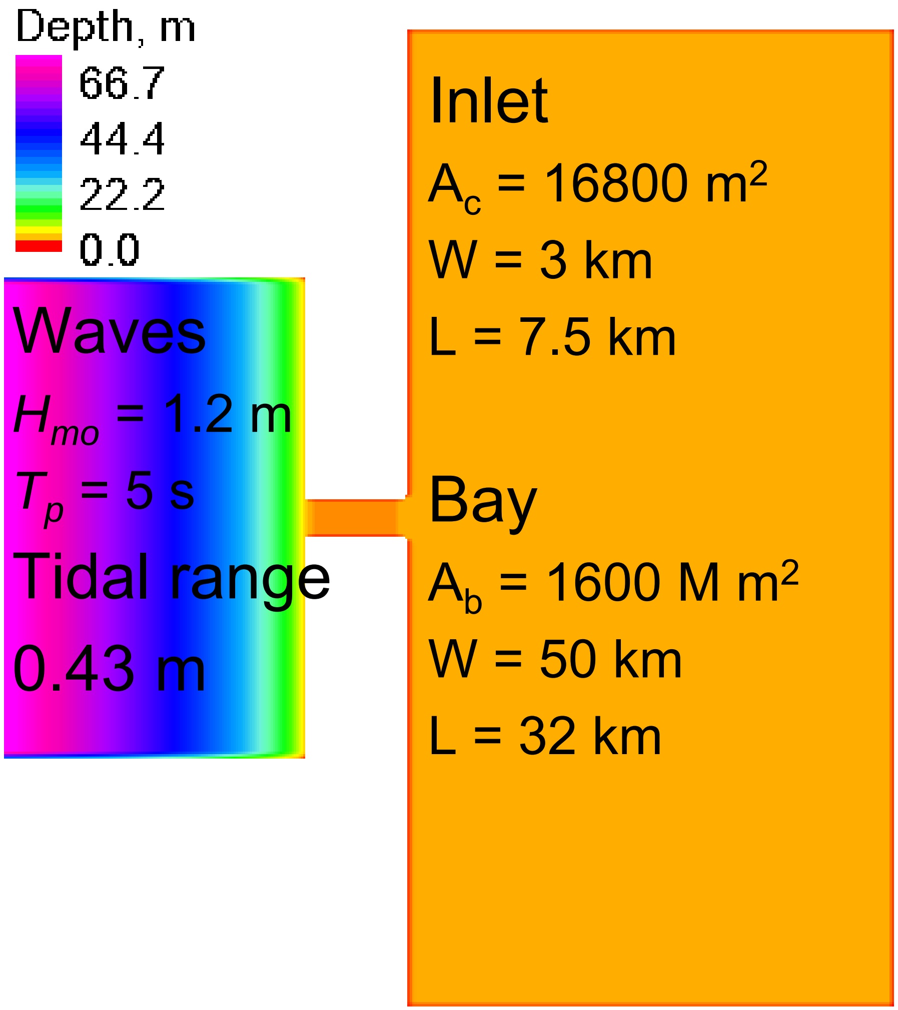


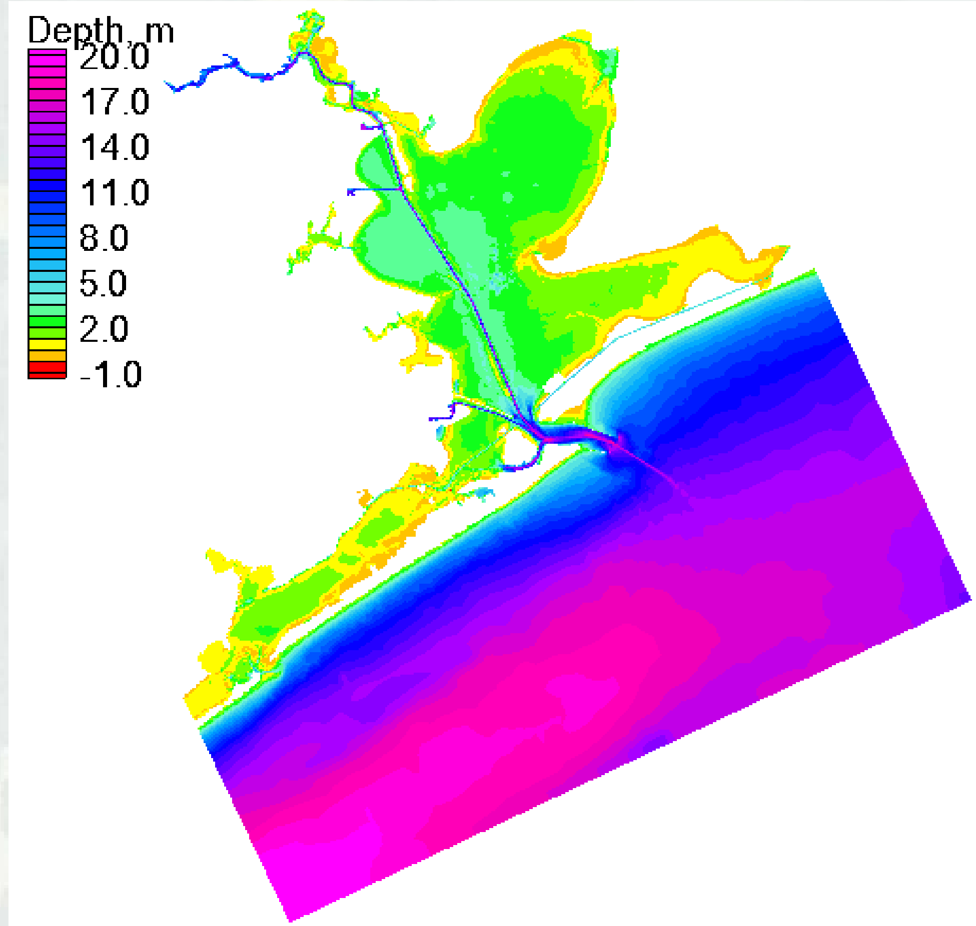
- Actual ebb shoal volume
  - ▶ 240 to 250 M m^3



Galveston, TX

Initial bathymetry





Results: Galveston, TX

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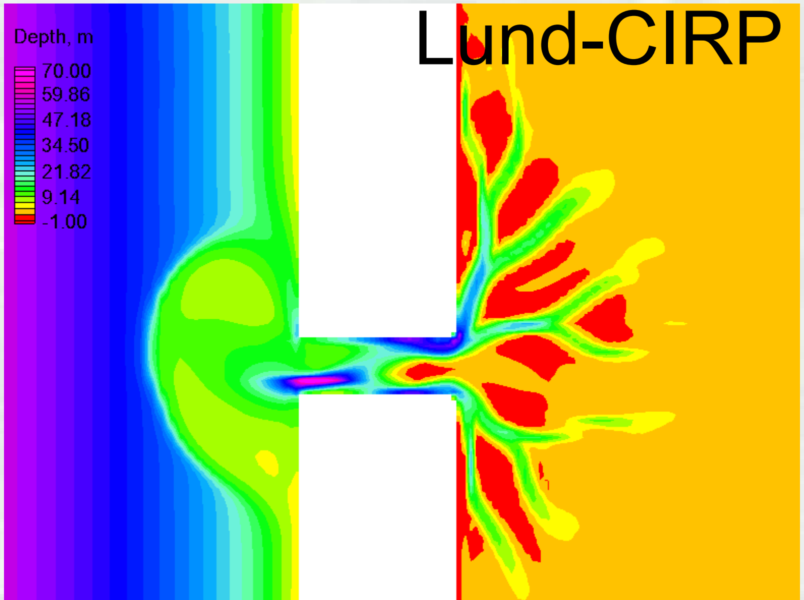

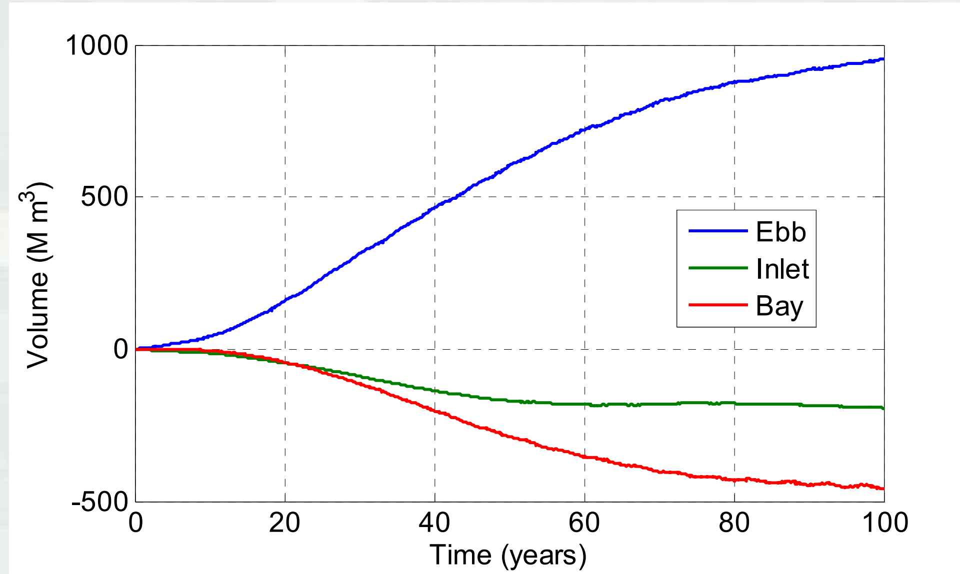

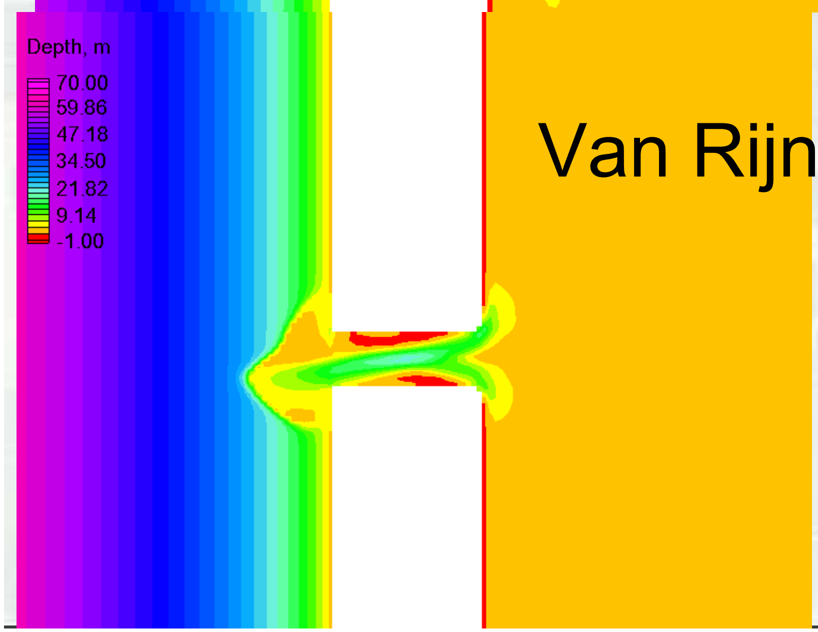

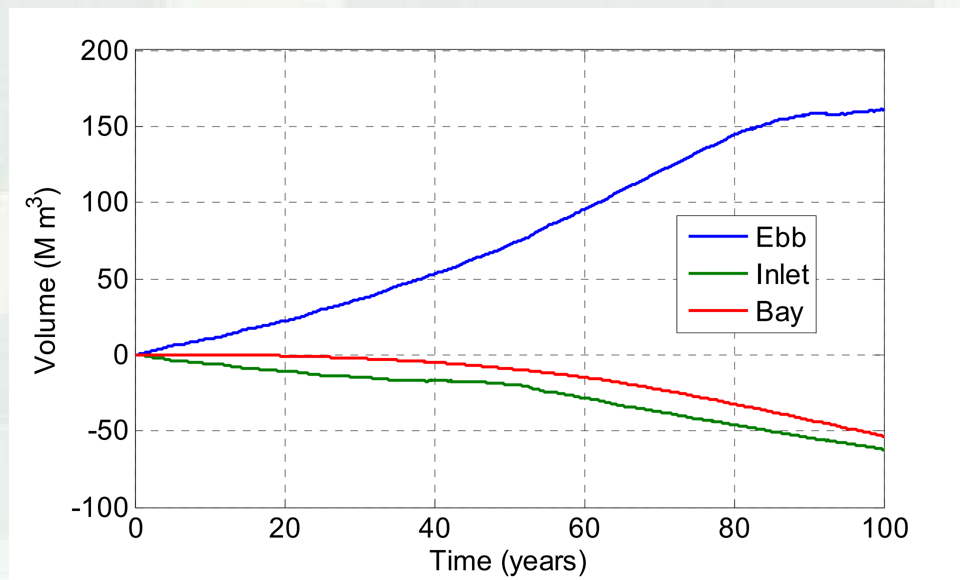

Results: Galveston, TX

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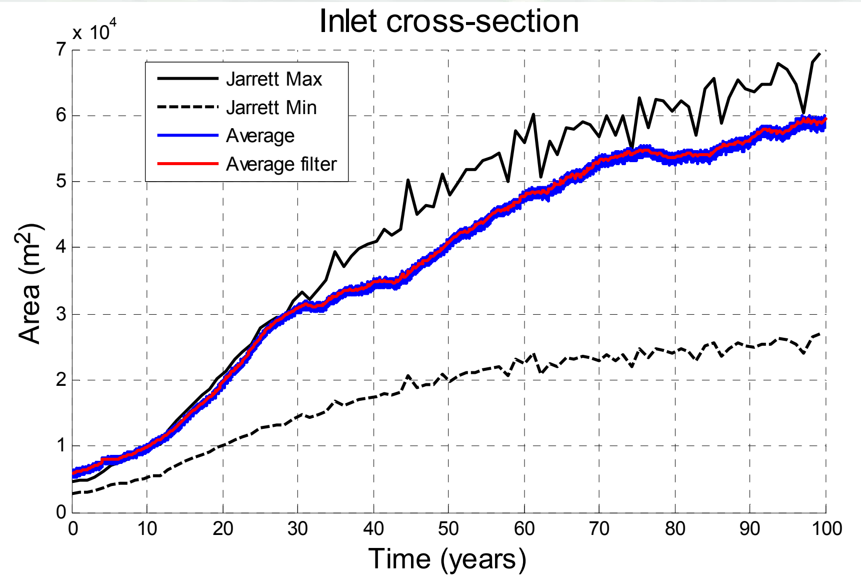
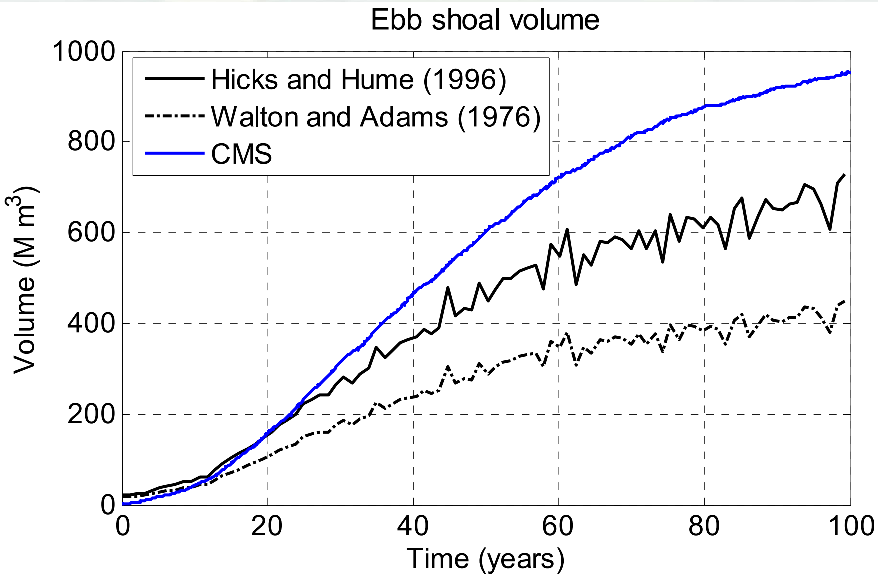
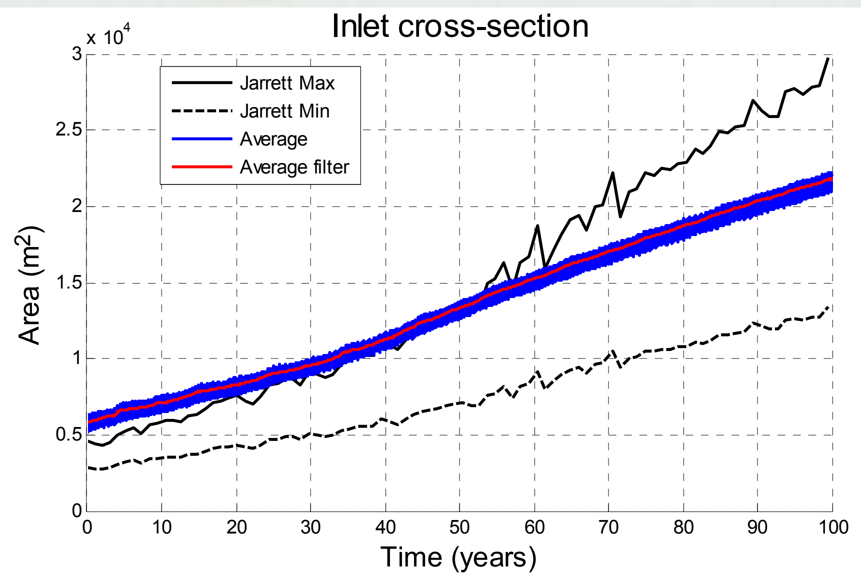
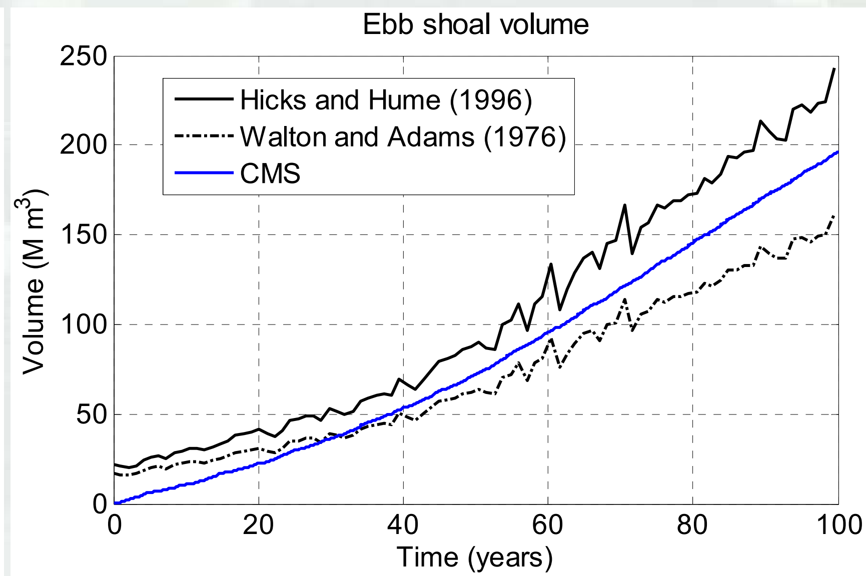




Van Rijn





Discussion and Conclusions

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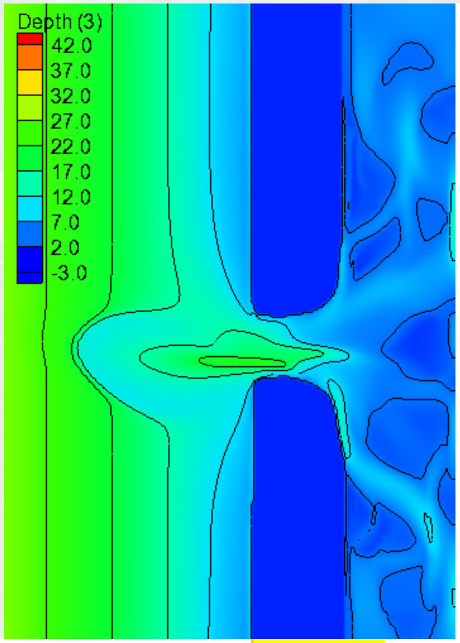
- Rate of bed change within the first 10-20 years is rapid and then slows
- None of the simulated inlets reached a full dynamic equilibrium after 100 years suggesting that either:
    1. The adaptation time of the simulated inlets is longer than 100 years
    2. The inlets may never reach equilibrium due to missing or incorrect processes necessary for a stable equilibrium
- Significantly different results were obtained for different sediment transport capacity formula

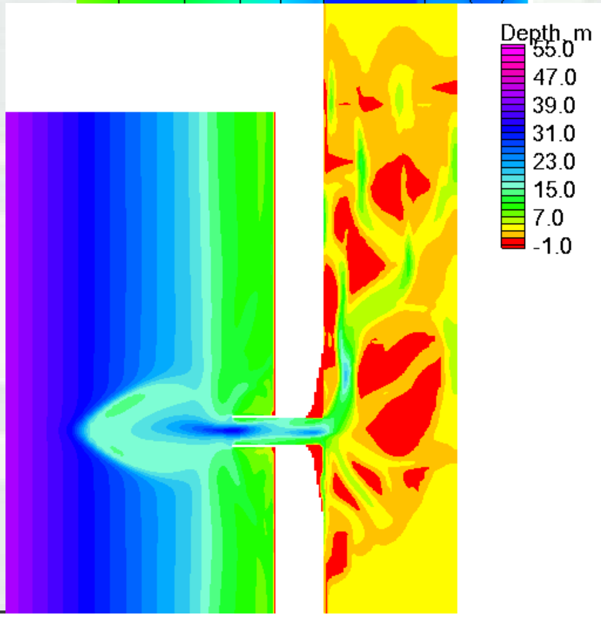
Discussion and Conclusions

- Model computational times were reasonable
  - 100 years in about 7-10 days on a PC
- Model stability was very reasonable
- Cross-sectional areas were generally over-predicted
- Ebb and flood shoal morphologies and evolution were reasonable
- Comparison to the Escoffier curves were reasonable

Future Work

- Multiple grain sizes
  - Reduce channel erosion
  - Help reach dynamic equilibrium faster
- Dynamic roughness
  - Function of the bed gradation and bedforms
- Bank erosion feature
- Influence of jetties, asymmetric bays, and dredging
- Inlet infilling and closure?





CIRP
Mission Support
Technology Transfer
Research & Development

CHL
Coastal and
Hydraulics
Laboratory

Thank you

Questions?